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Report 1777

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PERFORMANCE OF WAKE-ADAPTED PROPELLERS IN OPEN-WATER AND PROPULSION CONDITIONS AS DETERMINED BY THEORY AND EXPERIMENT

by

John L. Beveridge

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HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Some important considerations and concepts concerned with determining propeller performance in open-water and propulsion (behind-body) conditions are discussed. Two wake-adapted propellers were designed by the Eckhardt-Morgan method using Lerbs' theory of moderately loaded propellers. Performance of these propellers in open-water and wake-adapted conditions was calculated by the Burrill method. For the examples of a submerged body of revolution and a single-screw surface ship, relative rotative efficiencies as obtained by theory and model experiment are shown to be in good agreement.

INTRODUCTION

Various aspects of propulsion interaction are being studied at the David Taylor Model Basin with the support of the Bureau of Ships Fundamental Hydromechanics Research Program. In view of the general use of the propulsive coefficient and its components as a means of analyzing propulsion experiments, it is profitable to study these quantities analytically. To this end theoretical calculations and experiments were performed to determine propeller efficiency in open water, behind a submerged body of revolution, and behind a single-screw surface ship. The principal purpose of the present work is to compare propeller performance obtained by both theory and experiment. Burrill's[1] method, which employs Goldstein factors in determining induced velocities, is used for calculating propeller performance in open-water and behind-body conditions. For comparison purposes, Lerbs'[2] theory of moderately loaded propellers is used for the solution of the optimum propeller performance problem for the behind-body condition since this theory is a part of the Eckhardt-Morgan[3] propeller design method used in designing the propellers.

Burrill and Yang[4] computed open-water propeller efficiency and behind-body propeller efficiency for twin-screw and single-screw ships utilizing several definitions of advance coefficient (or inflow velocity); however, no experimental data were presented in connection with these results. An examination of the virtual propeller efficiency as computed

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[1] References are listed on page 18.

in Reference 4 reveals that it is assessed in the same manner as the efficiency for the propeller, when working in a variable wake, given in this report.

The prinicpal limitations and assumptions involved in this investigation are:

1. Circumferential wake variations (when they occur) and their effect on the elemental forces acting at the propeller blade sections are not considered; i.e., at each blade radius the local wake represents a mean value in the circumferential direction.

2. It is assumed in the Burrill solution of the inverse propeller problem that the Goldstein factors may be applied for both optimum and nonoptimum circulation distributions. Lerbs' theory of moderately loaded propellers applies to an arbitrary circulation distribution.

3. As presented, the method does not consider the gain in propeller efficiency that might occur when a rudder is placed in the propeller slipstream. This limitation is restrictive when comparing the results obtained from theory and experiment in the example of the surface ship. Propulsion tests of the body of revolution were conducted with the basic bare hull.

4. It is recognized that differences in factors such as the extent of turbulence and test Reynolds number between open-water and propulsion tests might be important in some cases. It is believed that estimates of relative rotative efficiency may be caculated for bodies with nonseparating flow. Of course, if tests are not conducted above a critical Reynolds number and the open-water test arrangement presents obvious flow interferences with respect to the propeller, then the relative rotative efficiency assumes the role of an arrangement factor.

CONCEPT OF PROPELLER RELATIVE ROTATIVE EFFICIENCY

From a propulsion viewpoint the performance of a body and propeller system may be analyzed by means of the propulsive coefficient η_D and its components.[5] Assuming that $V_o^* = V_a$ and $n_o = n$, η_D may be expressed as:

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*Subscript o indicates open-water value.

$$\eta_D = \frac{P_E}{P_D} = \frac{R_T V}{2\pi Q n} = \frac{R_T V}{T\ V_a} \cdot \frac{T_o\ V_o}{2\pi Q_o n_o} \cdot \frac{T\ Q_o}{T_o Q} \qquad [1]$$

where P_E is effective (towrope) power,

P_D is power delivered to the propeller,

R_T is hull resistance without propeller,

T is propeller thrust,

Q is propeller torque,

V is ship speed,

V_a is propeller effective speed of advance, and

n is propeller rate of revolution.

Reading from left to right, each factor on the right-hand side of Equation [1] is known as follows:

1. Hull efficiency $(\eta_H) = \dfrac{R_T V}{T V_A} = \dfrac{1-t}{1-w}$,

where t is the thrust-deduction coefficient and w is an effective wake fraction.

2. Propeller open-water efficiency $(\eta_o) = \dfrac{T_o V_o}{2\pi Q_o n_o}$.

3. Propeller relative rotative efficiency $(\eta_R) = \dfrac{T Q_o}{T_o Q}$.

For the case of thrust identity, where $T_o = T$, which is the case considered here, η_R is equal to $\dfrac{Q_o}{Q}$. Methods for estimating thrust deduction and wake fraction have been treated elsewhere.[6] Relative rotative efficiency is defined by $\eta_R = \dfrac{\eta_B}{\eta_o}$, where η_B is propeller efficiency for the behind-body condition. R. E. Froude[7] proposed this definition of η_R and described its physical meaning and significance.

The concept of relative rotative efficiency, η_R, arises in the use of the familiar Froude synthesis of propeller open-water test results and propulsion test results. In practice, η_R may be obtained indirectly from propulsion test data by the relation between the propulsive coefficient and its components; see Equation [1]. That is, using experimental values of effective and shaft horsepower, hull efficiency, and open-water propeller efficiency, η_R is calculated as a derived quantity from Equation [1]. This means that, except for test error, η_R represents the effects of dissimiliarity in flow conditions on the propeller behind the body and in open water (see Introduction, Assumption 4).

PROPELLER EFFICIENCY

THEORETICAL APPROACH

When wake data are available, it is possible to compute both open-water and behind-body propeller efficiencies from existing propeller theory.[1,3] The procedure for calculating propeller efficiency is based on an integration* of the propeller thrust and torque loading distribution. It is well to recall at this point that for a given ship the propulsive coefficient of Equation [1] and not the propeller efficiency in the behind-body condition is the criterion for optimizing the propulsion performance of a body and propeller system. Based on the foregoing, propeller efficiency for the behind-body condition may be estimated from the relation

$$\eta_B \approx \eta_o \cdot \eta_R \approx \frac{\int_{hub}^{1} (1 - \epsilon \tan \beta_i)(1 - w_x) \frac{dC_{TSi}}{dx} dx}{\int_{hub}^{1} \left(1 + \frac{\epsilon}{\tan \beta_i}\right) \frac{dC_{PSi}}{dx} dx} \qquad [2]$$

where the propeller nonviscous thrust-load and power coefficients, C_{TSi} and C_{PSi} are nondimensionalized on ship speed

ϵ is the section drag-lift ratio,

β_i is the hydrodynamic pitch angle,

---

*Only one integration need be performed since a design is based either on constant thrust or on constant power.

x is the radius fraction, and

$(1-w_x)$ is the circumferential average wake factor at radius x.

Equation [2] was evaluated, using Lerbs' theory of moderately loaded propellers, during the design of the two propellers considered here.

Next, consider wake-adapted propeller performance in open water. Propeller performance characteristics in open water are of considerable interest, particularly for systematic propeller series and for ship powering estimates where the familiar concept of an effective speed of advance is introduced. In this analysis, Burrill's[1] method was used to calculate performance of the given propellers when operating in a given flow.

The computations are programmed for the IBM-704 computer. Since, ultimately, the ratio of propeller efficiency in the wake (behind-body condition) to propeller efficiency in open water, $\frac{\eta_B}{\eta_o} = \eta_R$, is desired, the Burrill method was used to calculate in a consistent manner both propeller efficiencies. Theoretically, however, the Goldstein factors do not apply (see Introduction, Assumption 2) to the behind-body efficiency. It should be emphasized that the propeller efficiency for the behind-body condition is calculated rigorously by the use of Lerbs' theory of moderately loaded propellers. For the examples presented and discussed (that is, a submerged body of revolution and a surface ship) behind-body propeller efficiency is computed by both methods.

EMPIRICAL APPROACH

An alternate approach in determining the open-water efficiency of a wake-adapted propeller is as follows: It is assumed that the propeller was designed for wake-adapted operation and, consequently, a distribution of $\tan \beta_i$, dC_{TSi}, and dC_{PSi} is available. The behind-body propeller efficiency is obtained from Equation [2], using the prescribed wake distribution. To calculate open-water propeller efficiency, using the elementary thrust and power coefficients appropriate to the behind-body condition, the radial wake distribution is replaced by a constant factor (1-w), in the numerator, called the effective velocity ratio. The effective wake fraction w, which is obtained by the usual Froude synthesis or estimated by other means, arises essentially from two causes:

1. The propeller blade sections (wake-adapted calculation) do not experience the same distribution of $\tan \beta_i$, dC_{TSi}, and dC_{PSi} in open water.

2. An alteration of the flow about the body due to the presence of the working propeller. Viewed as a potential problem, this is equivalent to adding an additional disturbing singularity to satisfy the boundary conditions on the body surface due to the propeller-induced velocities. Since this approach is essentially empirical, it will not be discussed further except to note that, in general, good results may be expected from this procedure, and in the two examples discussed, precise agreement with experimental results was obtained.

EXAMPLES AND DISCUSSION

SUBMERGED BODY OF REVOLUTION

A five-bladed wake-adapted propeller (TMB 3836) was designed by Lerbs' theory of moderately loaded propellers and the method given in Reference 3, to operate behind a submerged body of revolution of 7.3 fineness ratio (see Figures 1 and 2). In addition to the design calculations, propeller efficiencies were determined by experimentation and by computation using the Burrill method for both the open-water and behind-body conditions. The necessary input data (wake-adapted) for Equation [2] are given in Table 1, and the output data from the IBM-704 computer using the Burrill method is given in Table 2. Graphs of the open-water characteristics and K_T versus K_Q for propulsion conditions are given in Figure 4.

TABLE 1

Propeller 3836, Input Data for Equation [2] from Design Calculations

x	$1-w_x$	$\tan \beta_i$	ϵ	$10 \frac{dC_{TSi}}{dx}$	$10 \frac{dC_{PSi}}{dx}$
0.2	0.495	1.810	------	0.000	0.000
0.3	0.613	1.342	0.0186	1.086	0.898
0.4	0.687	1.066	0.0197	2.030	1.777
0.5	0.748	0.890	0.0235	2.923	2.671
0.6	0.799	0.766	0.0297	3.264	3.423
0.7	0.845	0.675	0.0379	4.030	3.914
0.8	0.886	0.605	0.0459	4.022	4.001
0.9	0.925	0.550	0.0555	3.326	3.381
1.0	0.963	0.505	------	0.000	0.000
Design K_T = 0.192					

TABLE 2

Characteristics for Propeller 3836 as Computed by the Burrill Method

Open-Water Characteristics			Behind-Body Characteristics	
J	K_T	10 K_Q	K_T	10 K_Q
1.525	0.094	0.291	0.071	0.220
1.387	0.221	0.460	0.164	0.443
1.272	0.222	0.578	0.229	0.588
1.090	0.297	0.726	0.280	0.684
0.954	0.347	0.808	0.319	0.753
			0.369	0.834
			0.402	0.881

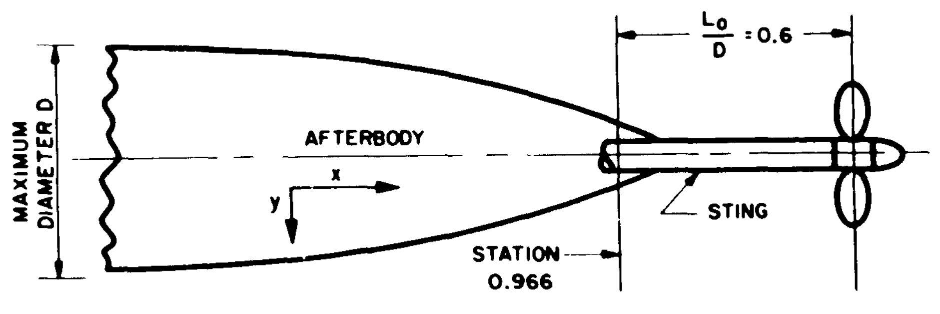

Figure 1 - Schematic Drawing of Propeller Location Relative to Body of Revolution

Number of Blades ... 5

Exp. Area Ratio .. 0.505

MWR 0.198

BTF 0.042

P/D (At 0.7R) 1.567

Diameter .... 12.263 in.

Pitch (At 0.7R).. 19.211 in.

Rotation .... R.H.

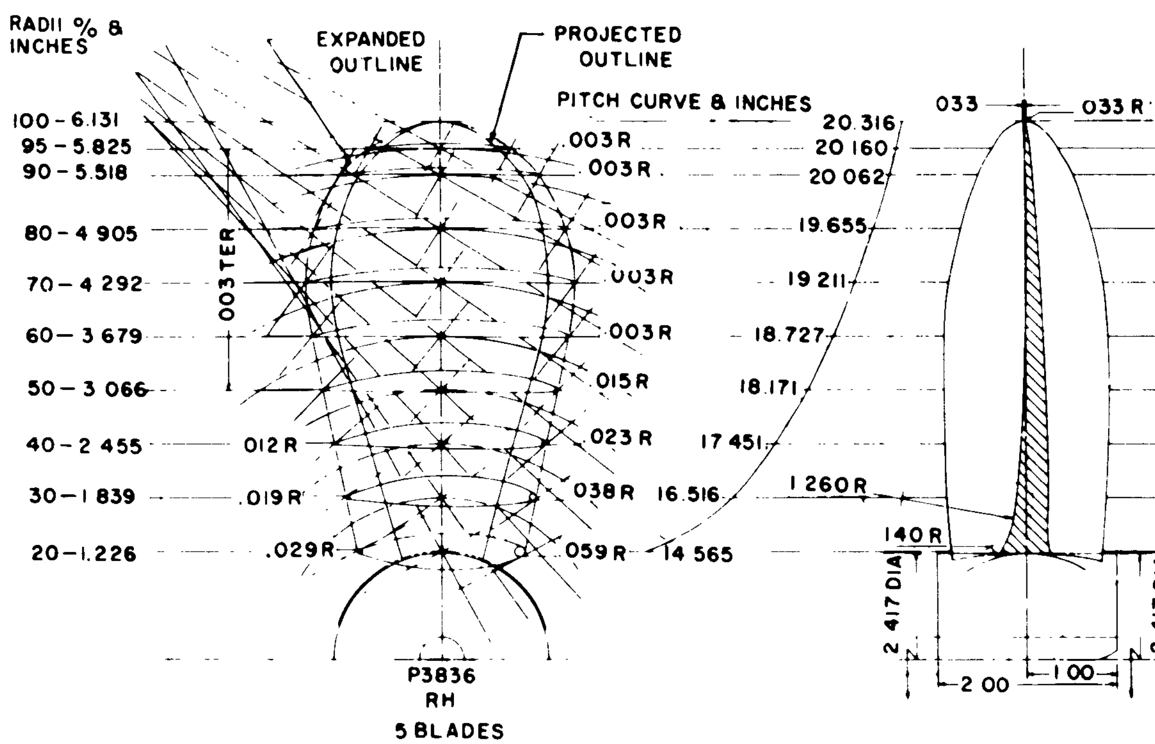

Figure 2 - Propeller 3836

The following experimental and computed results were obtained with Propeller 3836 for the several propeller efficiencies:

Propeller Efficiencies	Computed Results		Experimental Results
	Burrill	Lerbs' Induction Factors	
Open water, η_o	0.86	0.83*	0.82
Behind body, η_B	0.81	0.78	0.77
Relative rotative, η_R	0.94		0.94

As seen from the data presented, experimental verification was obtained for the relative rotative efficiency. Good agreement with the experimental results was obtained for both the separate open-water efficiency η_o and the behind-body efficiency η_B by using the design calculations of Table 1 and η_R predicted from the Burrill calculations to obtain η_o. In contrast, the separate propeller efficiencies obtained from the Burrill method are four points higher than the comparable experimental values. This could be due to the fact that Propeller 3836 has an unusually high pitch ratio, $(P/D)_{0.7} = 1.57$; the Burrill method might be expected to give better results for more moderately pitched propellers.

SURFACE SHIP

Propeller efficiencies for surface ships may be calculated from Equation [2] by utilizing the total wake including a wave component. Undoubtedly, the numerical integration of a circumferentially nonuniform wake is different from that performed by a propeller. However, it is of practical and academic interest to obtain computed and experimental results for a typical single-screw surface ship. For this purpose, a four-bladed wake-adapted propeller TMB 3471 which was designed by the method given in

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*Derived from $\eta_o = \frac{\eta_B}{\eta_R}$, assuming $\eta_R = 0.94$.

Reference 3 for the Mariner-class merchant ship, was chosen as an example; see Figure 3. In a manner similar to that for the body of revolution, the necessary input data (behind-body condition) for Equation [2] are tabulated in Table 3 for a ship speed of 21 knots; the results from the Burrill method are given in Table 4. Graphs of the open-water characteristics and K_T versus K_Q for propulsion conditions are given in Figure 5.

TABLE 3

Propeller 3471, Input Data for Equation [2] from Design Calculations

x	$1-w_x$	$\tan \beta_i$	ϵ	$\frac{dC_{TSi}}{dx}$	$\frac{dC_{PSi}}{dx}$
0.2	0.576	1.414	------	0.0000	0.000
0.3	0.656	1.005	0.0195	0.246	0.234
0.4	0.712	0.786	0.0202	0.465	0.463
0.5	0.751	0.646	0.0226	0.685	0.700
0.6	0.779	0.548	0.0258	0.882	0.917
0.7	0.800	0.476	0.0294	1.037	1.092
0.8	0.815	0.421	0.0328	1.108	1.181
0.9	0.826	0.376	0.0373	0.991	1.062
1.0	0.837	0.341	------	0.000	0.000
Design K_T = 0.212.					

Prop. No.	Linear Ratio	Dia. Model in.	Dia. Ship in.	Pitch Model in. @ 70 %	Pitch Ship in. @ 70 %	Pitch Ratio @ 70 %	Number of Blades	Exp. Blade Area
3471	24.175	10.424	252.00	11.977	289.548	1.149	4	43.672

E.A / D.A	M.W.R.	Proj. Area	P.A. / D.A	B.T.F.	Rake Angle deg	Rotation	Ship Model	Pattern Block Pitch
.512	.250	34.120	.400	–	7.50	RH	–	–

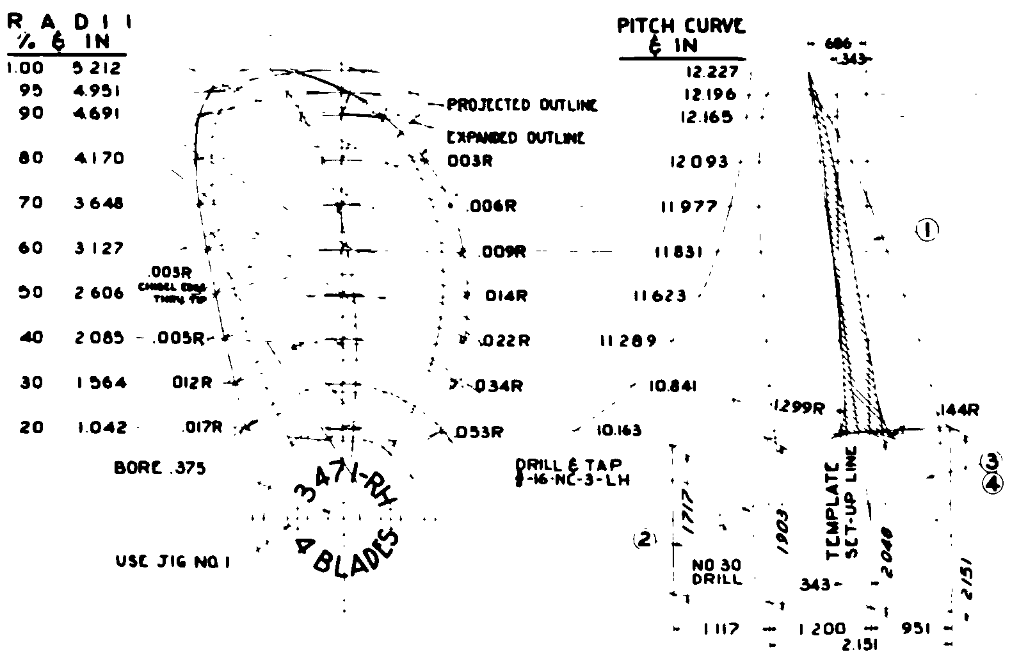

Figure 3 - Propeller 3471

TABLE 4

Characteristics for Propeller 3471 as Computed by the Burrill Method

Open-Water Characteristics			Behind-Ship Characteristics	
J	K_T	$10\ K_Q$	K_T	$10\ K_Q$
1.205	0.054	0.148	0.194	0.387
0.938	0.180	0.368	0.266	0.488
0.844	0.217	0.423	0.287	0.514
0.768	0.245	0.463	0.303	0.533
0.704	0.265	0.488	0.315	0.540
0.604	0.295	0.525	0.332	0.557
0.563	0.305	0.535	0.337	0.563

The following experimental and computed results were obtained with Propeller 3471 for the several propeller efficiencies:

Propeller Efficiencies	Computed Results		Experimental Results
	Burrill	Lerbs' Induction Factors	
Open water, η_o	0.68	0.69*	0.70
Behind body, η_B	0.69	0.70	0.70
Relative rotative, η_R	1.01		1.00

As seen from the data presented, computed and experimental efficiencies are in good agreement. In fact, the open-water efficiency and behind-body efficiency according to the Burrill method are only two points and one point lower, respectively, than the experimental values. Note that the agreement is considerably better than that obtained in the example of the body of revolution with Propeller 3836 which has a high pitch ratio of 1.57. Propeller 3471 has a pitch ratio of 1.15.

Two important points may be observed from the results: (1) behind-body efficiency η_B predicted by the Burrill method agrees well with the design calculations and (2) the relative rotative efficiency η_R is essentially unity. However, it would normally be expected that the experimental value of η_R would be a few points greater (compared to the calculated value of η_R) due to the favorable effect of the rudder[8] installed behind the propeller for the propulsion test. The computed results do not consider the gain in efficiency that might occur when a rudder is placed in the propeller slipstream.

*Derived from $\eta_o = \frac{\eta_B}{\eta_R}$, assuming $\eta_R = 1.01$.

CONCLUSIONS

In summarizing the results obtained for the examples of a submerged body of revolution and a single-screw surface ship, it seems reasonable to conclude that:

1. Propeller relative rotative efficiency defined as the ratio of propeller efficiency in the behind-body condition to that in the open-water condition may be accurately calculated, as evidenced by experimental verification, using the Burrill method.

2. When compared to experimental data, better results were obtained for the behind-body propeller efficiency from the design calculations, using the Eckhardt-Morgan design method, than were predicted by the Burrill method.

3. The Burrill method gave better results for separate open-water and behind-body propeller efficiencies in the case of the more moderately pitched surface ship propeller.

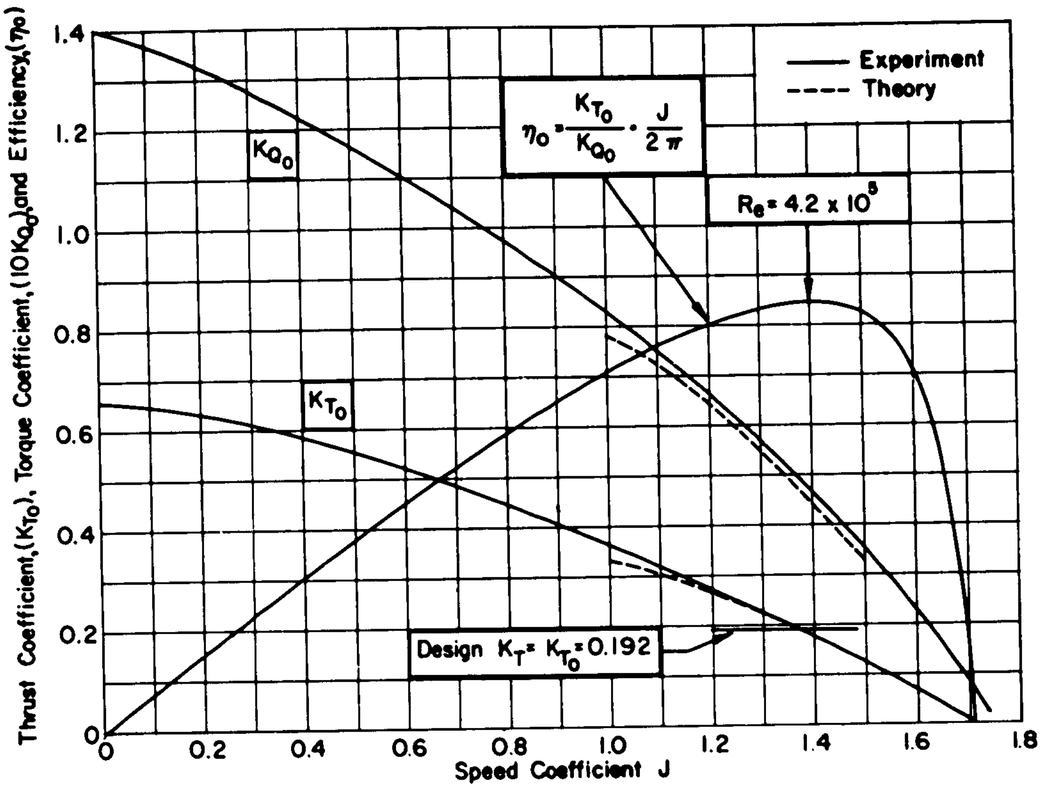

Figure 4a - Open-Water Condition

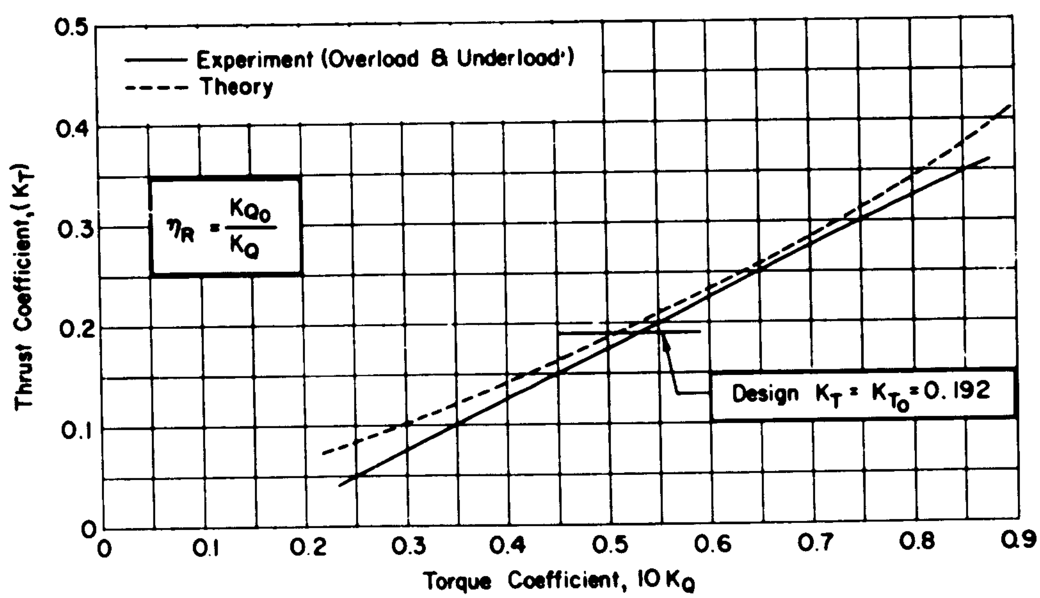

Figure 4b - Behind-Body Condition

Figure 4 - Characteristic Curves for Propeller 3836

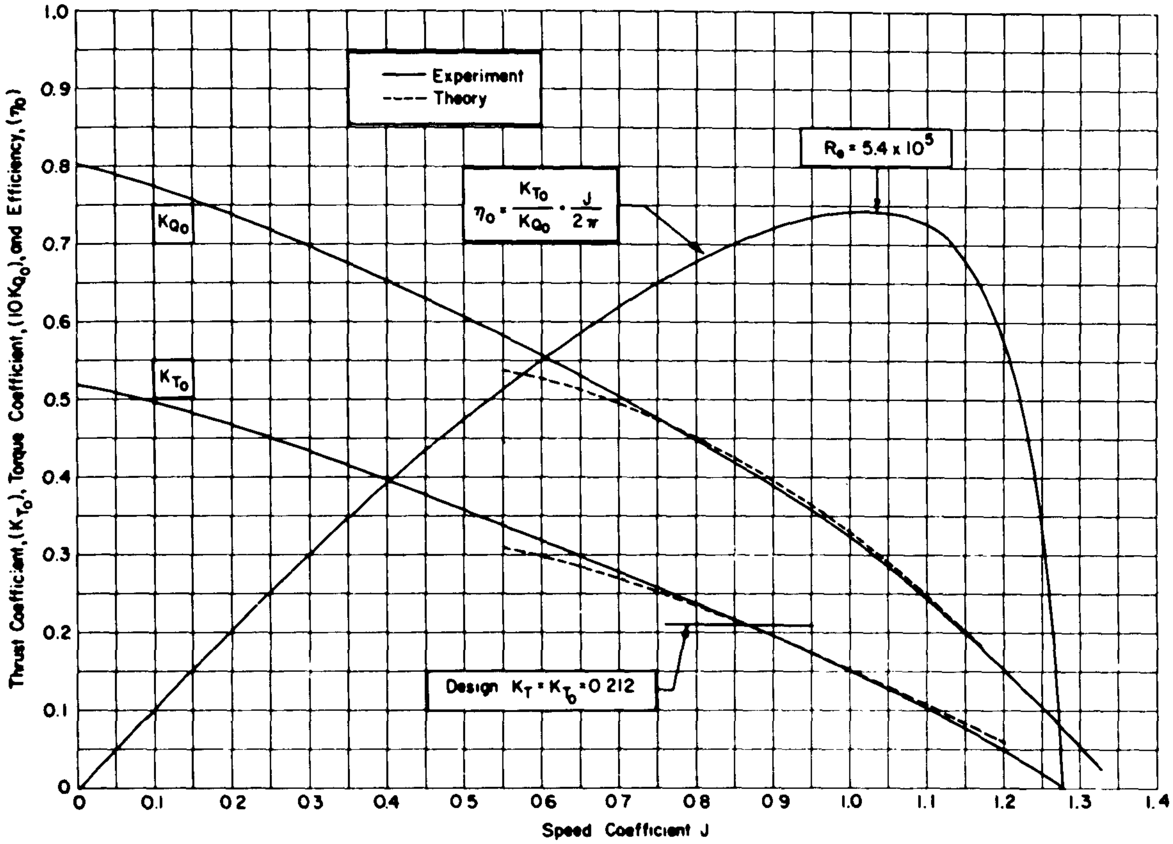

Figure 5a - Open-Water Condition

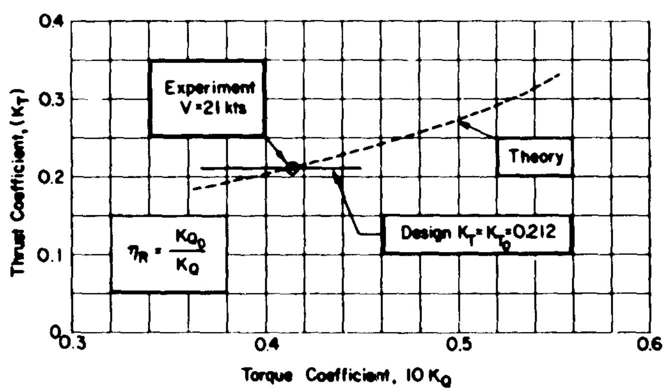

Figure 5b - Behind-Body Condition

Figure 5 - Characteristic Curves for Propeller 3471

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